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DESIGN AND ANALYSIS OF A STATISTICAL EXPERIMENT ON HIGH VOLTAGE BREAKDOWN IN VACUUM

by

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February 1968

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Abstract

The results of an experiment designed as a quarter replicate of a 2^7 plan on factors effecting high-voltage breakdown in vacuum are given. The significance of each of the seven factors is analyzed, showing the effect of electrode materials, electrode geometry, electrode finishes, and the bakeout process. A good degree of confidence was obtained showing that the anode material and anode geometry are important in the cause for breakdown.

The results of these statistically designed experiments and other experiments performed investigating the activity in high-voltage gaps lead to the conclusion that anode effects play a major role in the breakdown process.

Upon completion of the full line of designed experiments, the information gained from this work will be compiled in charts and graphs as a design monograph for the high-voltage high-vacuum component design engineer.

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ON HIGH-VOLTAGE BREAKDOWN IN VACUUM

INTRODUCTION

The problem of high-voltage breakdown in vacuum has been studied for more than forty years. From these studies many conflicting theories have evolved that still do not reliably define a breakdown criterion nor explain the mechanisms involved in the process. High-voltage breakdown in vacuum has received renewed interest in recent years because of the demands for superpower radar system components, ion thrusters for space propulsion, and high-energy particle accelerators.

The study of the factors that effect a high-voltage breakdown in vacuum is being performed at this laboratory using statistically designed experiments. Initially, the sixteen factors shown in Table I were defined as probable contributors to the breakdown process:

TABLE I - FACTORS EFFECTING BREAKDOWN

Inflexible Factors	Flexible Factors
1. Cathode Material	12. Residual Gas Pressure
2. Anode Material	13. Energy of Supply
3. Cathode Finish	14. Contaminant
4. Anode Finish	15. Magnetic Field
5. Cathode Geometry	16. Electrode Spacing
6. Anode Geometry	
7. Vehicle Bakeout	
8. Envelope Material	

The objective of this program is to analyze the significance of each of these factors as well as their interactions.

EXPERIMENTAL PROCEDURE

The first designed experiment was carried out using seven of the inflexible factors, each at two levels, in a 2^{7-2} plan (Table II) derived from Table M of Davies' Design and Analysis of Industrial Experiments:

TABLE II - INFLEXIBLE FACTOR LEVELS INVESTIGATED

Factor	Levels
CATHODE MATERIAL	Ti-7AL -4Mo
	304-SS
	OFHC Cu
ANODE MATERIAL	Ti-7AL -4Mo
	304-SS
	OFHC Cu
CATHODE FINISH	COARSE
	FINE
ANODE FINISH	COARSE
	FINE
CATHODE GEOMETRY	SPHERE
	PLANE
ANODE GEOMETRY	SPHERE
	PLANE
VEHICLE BAKEOUT	ABSENT
	PRESENT

Table III shows the levels of each factor for each of the thirty-two treatments. The minus sign in each treatment means that the factor is either at the low level or absent from the treatment; the plus sign means that the factor is at the high level or present in the treatment. The set is orthogonal; each leve of any factor is tested equally against each of the other factor level combinations:

TABLE III - 2^{7-2} PLAN

TREATMENT	A	B	C	D	E	F	G
(1)	−	−	−	−	−	−	−
acf	+	−	+	−	−	+	−
bcf	−	+	+	−	−	+	−
ab	+	+	−	−	−	−	−
df	−	−	−	+	−	+	−
acd	+	−	+	+	−	−	−
bcd	−	+	+	+	−	−	−
abdf	+	+	−	+	−	+	−
ce	−	−	+	−	+	−	−
aef	+	−	−	−	+	+	−
bef	−	+	−	−	+	+	−
abce	+	+	+	−	+	−	−
cdef	−	−	+	+	+	+	−
ade	+	−	−	+	+	−	−
bde	−	+	−	+	+	−	−
abcdef	+	+	+	+	+	+	−
fg	−	−	−	−	−	+	+
acg	+	−	+	−	−	−	+
bcg	−	+	+	−	−	−	+
abfg	+	+	−	−	−	+	+
dg	−	−	−	+	−	−	+
acdfg	+	−	+	+	−	+	+
bcdfg	−	+	+	+	−	+	+
abdg	+	+	−	+	−	−	+
cefg	−	−	+	−	+	+	+
aeg	+	−	−	−	+	−	+
beg	−	+	−	−	+	−	+
abcefg	+	+	+	−	+	+	+
cdeg	−	−	+	+	+	−	+
adefg	+	−	−	+	+	+	+
bdefg	−	+	−	+	+	+	+
abcdeg	+	+	+	+	+	−	+

The letter assignments, shown in Table IV, were carefully chosen so that in the treatment and analysis of the results the effect of any two-factor interaction involving the bakeout factor, D, would be clear of any other main effect or two-factor interaction of interest:

TABLE IV - LETTER ASSIGNMENT

A - Anode Material	D - Bakeout
B - Cathode Shape	E - Anode Shape
C - Cathode Material	F - Anode Finish
G - Cathode Finish	

The treatments were randomized and performed in the test vehicle shown in Fig. 1:

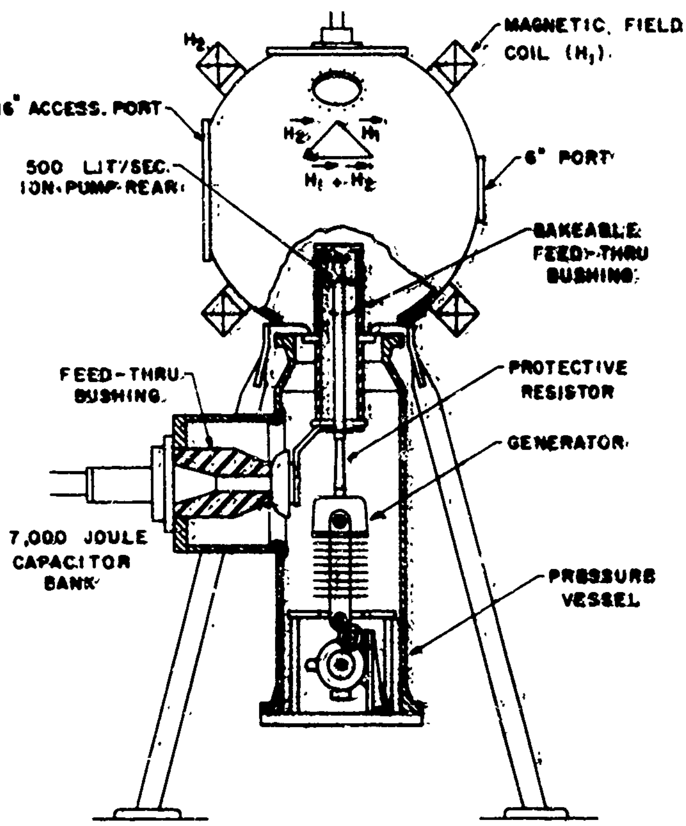

Fig. 1 Test Vehicle

Each treatment was carried out in this manner: The voltage was increased in 10-kV steps, each step held for two minutes. During this procedure, the microdischarges (self-quenching pulses of current), hydrogen evolutions, X-radiation, visible radiation, and prebreakdown current were monitored. The voltage was increased in this stepwise manner until puffs of hydrogen were detected by the mass spectrometer. This voltage was recorded. After the gap was outgassed again, the increase of voltage was continued until sparking occurred. This voltage was recorded as the first breakdown voltage. This procedure was repeated for each treatment at six electrode separations from 0.5 to 3.0 cm. During the application of voltages at each gap setting, the sparking and gas evolution conditions the electrodes so that higher voltages may be held off. These higher voltages were also recorded for the analysis.

Thus, we have three sets of yields of voltages that can be incorporated as the inputs to the design plan for analysis. These numbers inserted in

the boxes of the design table and treated with the signs shown will give the deviation from the average of the whole experiment for each factor and factor interaction. The results can be obtained in a more systematic manner by using the Yates Algorithm, which consists of repeatedly adding and subtracting adjacent test results until the results for the mean, main effects and two-factor interactions are obtained, as shown in Table V:*

TABLE V - DEFINING RELATION

I = -ABDFG = -CDEFG = ABCE
YIELDS OF YATES ALGORITHM

1 mean	12 ABE + C	23 BDG - AF
2 A	13 DE	24 ABDG - F
3 B	14 ADE	25 EG
4 AB + CE	15 BDE	26 AEG
5 D	16 ABDE + CD	27 BEG
6 AD	17 G	28 ABEG + CG
7 BD	18 AG	29 DEG - CF
8 ABD - FG	19 BG	30 ADEG
9 E	20 ABG - DF	31 BDEG
10 AE + BC	21 DG	32 ABDEG - EF
11 BE + AC	22 ADG - BF	

This table shows that we can get seven main effects and six two-factor interactions with D (the bakeout) plus the mean. The others may be used for estimating error.

ANALYSIS OF RESULTS

The analysis was carried out using the Yates Algorithm with inputs of the voltages obtained. The results of this analysis indicated a low level of confidence for the effects. Therefore, the voltages were plotted versus distance to the one-half power, since these and many other experimental results have been found to follow this relationship. From these plots a slope was calculated and used as inputs to the Yates program. This slope, using the average of many points, smoothed out the values as well as the error and gave more significant results.

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* see Appendix

These results are plotted on half-normal graph paper as shown in Fig. 2:

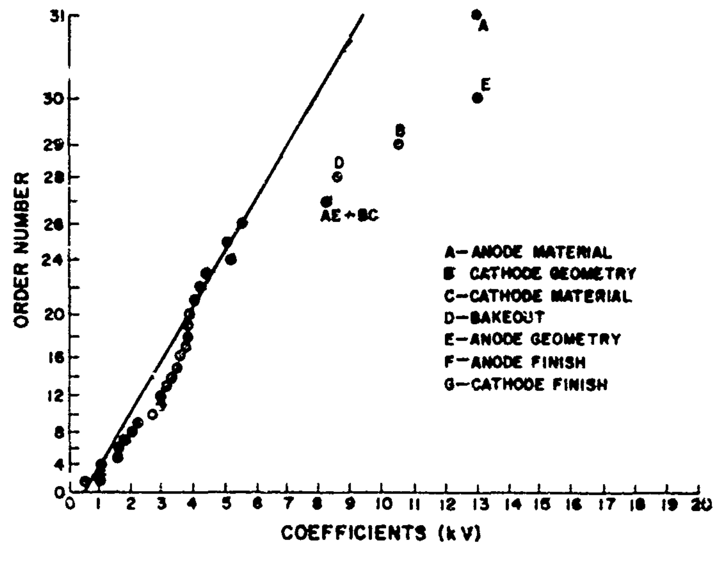

Fig. 2 Half-normal plot of coefficients obtained from the Yates Algorithm.

This graph is designed to give a straight line for any random process. The order number represents the range of values, from smallest to largest, corresponding to the coefficients obtained from the Yates analysis. Deviations from a straight line indicate that the factor has a significant influence on the distribution of the thirty-two values and that the values are other than random. This plot shows that a straight line can be drawn through most of the points that represent effects of the factors with little or no deviation from the average of the experiment. The points labeled A, E, B, D, and AE + BC are real effects, and the significance is indicated by the distance from the straight line. The AE + BC effect, however, does not donate any information because the AE cannot be distinguished from the BC effect. From this experiment these conclusions can immediately be drawn:

1. A and E (the anode material and geometry) are most important.

2. B (the cathode geometry) is important.

3. D (the bakeout factor) is important but less than the above.

This analysis is consistent with the results of experiments studying the mechanisms in the breakdown process, showing that the physical properties of the anode are a determining factor that initiates a breakdown in vacuum.[1,2]

The level of the anode geometry factor that raised the breakdown voltage is the spherical electrode. This might also be said for the cathode

geometry, but with less confidence. When the anode material was titanium alloy, higher breakdown voltages were reached than when it was copper. The bakeout factor, D, was pertinent to this experiment with the test vehicle designed for this study. The two levels of bakeout were complete system and electrode bakeout versus electrode only bakeout. The electrodes were equipped with internal heaters for this purpose. The complete system and electrode bakeout level is superior to electrode only bakeout for attaining higher breakdown voltages.

Along with the statistical analysis, the results of the experiment were analyzed as to the physical processes occurring in the highly stressed electrode system. As previously stated, the hydrogen partial pressures were monitored on the mass spectrometer. Large bursts of gas were coincident with sparking or breakdown. Also, the superiority of spherical electrodes in holding off higher voltages suggested a breakdown mechanism dependent on the amount of gas present in the gap and the pumping conductance of the electrode gap system caused by the shape and size of the electrodes and the gap distance. A theory was proposed whereby the gas conductance of the gap played a major part in the breakdown process.[3] Simply stated, small-area electrodes with a high-conductance gap will hold off higher voltages than large-area electrodes at the same gap spacing. To evaluate this theory, a second statistically designed block-of-eight experiment was derived. The objective of this experiment was to verify the gas pumping conductance theory. The factors chosen were anode processing, cathode processing, and electrode size. The two levels of electrode processing are hydrogen baked versus vacuum baked, and, for size, a 4" versus 4/3" diameter Bruce plane, as shown in a. of Table VI. Because of the simplicity of this full factorial 2^3 experiment, it was decided to incorporate a transverse magnetic field as a factor at the end of each treatment, as shown in b. of Table VI:

TABLE VI - FACTORS AND LEVELS FOR BLOCK-OF-EIGHT EXPERIMENT

a. Without Magnetic Field

Factor	Letter	Level: High	Level: Low
Anode Processing	A	a - Vacuum Baked	1 - Hydrogen Baked
Cathode Processing	B	b - Vacuum Baked	1 - Hydrogen Baked
Electrode Size	C	c - Large	1 - Small

b. With Magnetic Field

Factor	Letter	Level: High	Level: Low
Anode Processing	A	a - Vacuum Baked	1 - Hydrogen Baked
Cathode Processing	B	b - Vacuum Baked	1 - Hydrogen Baked
Electrode Size	C	c - Large	1 - Small
Perpendicular Magnetic Field	D	d - Present	1 - Absent

The treatment was repeated with magnetic field and then again without magnetic field to show up any consistent difference between the first and third breakdown voltages because of the application of the magnetic field. This is now a complete 2^4 factorial experiment and can be analyzed separately as two 2^3 experiments, as shown in Table VII:

TABLE VII - EXPERIMENTAL ORDER

Order	Description	Main Block	Perpendicular Fields
1	Anode 4-inch Bruce h-baked Cathode 4-inch Bruce h-baked	c	cd
2	Anode 4/3-inch Bruce h-baked Cathode 4/3-inch Bruce h-baked	(1)	d
3	Anode 4-inch Bruce vac-baked Cathode 4-inch Bruce h-baked	ac	acd
4	Anode 4/3-inch Bruce vac-baked Cathode 4/3-inch Bruce vac-baked	ab	abd
5	Anode 4/3-inch Bruce h-baked Cathode 4/3-inch Bruce vac-baked	b	bd
6	Anode 4-inch Bruce h-baked Cathode 4-inch Bruce vac-baked	bc	bcd
7	Anode 4-inch Bruce vac-baked Cathode 4-inch Bruce vac-baked	abc	abcd
8	Anode 4/3-inch Bruce vac-baked Cathode 4/3-inch Bruce h-baked	a	ad

The experiment was performed similarly to the stepwise voltage increase procedure as described before. The resulting voltages are plotted versus distance to the one-half power. In Fig. 3, first the average effect, μ, without magnetic field present, is plotted with the average effect, μ_t, with magnetic field present. It can be seen immediately that the magnetic field lowers the breakdown voltage except at the smallest spacing tested.

In Fig. 4, the effects of the factors, A_1, AE, and A_3 are shown by subtracting the values individually from the corresponding overall average breakdown value, μ. The subscript 1 refers to the conditioned breakdown value prior to applying magnetic field and 3 refers to the breakdown value after application of magnetic field. The differences in these values are indicative of a memory of the conditions imposed by the magnetic field after it was removed. Other main effects and two-factor interactions are plotted similarly.

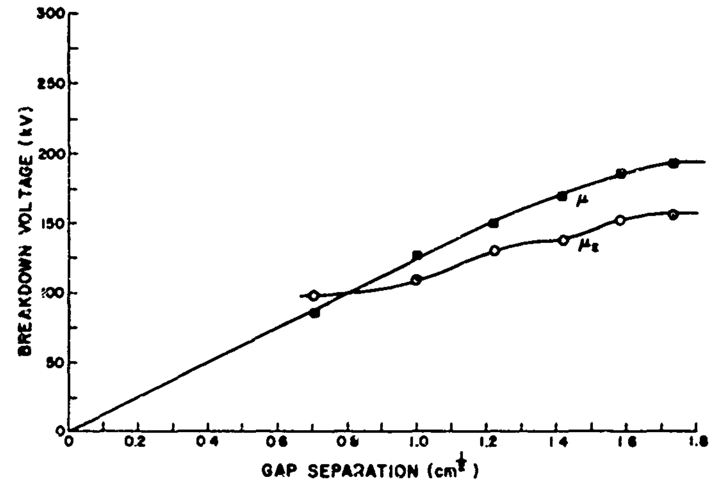

Fig. 3 Breakdown voltage versus gap separation in centimeters to the one-half power for average values with and without magnetic field.

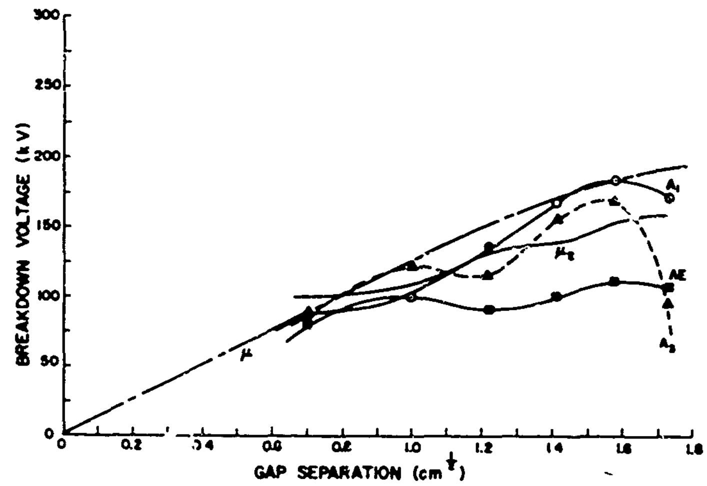

Fig. 4 Breakdown voltage versus gap separation in centimeters to the one-half power for average values with factor A and two-factor interaction AE.

From these curves, the principal conclusions that can be stated with a good measure of confidence are as follows:

1. The hydrogen-baking procedure permitted higher breakdown voltages than did the vacuum-baking. The magnetic field amplified this difference.

2. Large-area electrodes reduced the breakdown voltage, which is consistent with the results obtained in the first experiment. The magnetic field had no effect in this case.

3. The combined effect of hydrogen-baking of the cathode and using small electrodes raises the breakdown voltage. This effect is amplified in the presence of a magnetic field.

CONCLUSIONS

The results of these experiments, presented in this manner, show with a good degree of confidence what can be expected when electrodes are designed for high-voltage devices. These data are for copper electrodes. Other materials of interest to vacuum component design engineers will be similarly analyzed.

The next experiment (now being conducted) was designed as a full factorial with six factors at two levels, as a result of some three-factor interactions showing up in the analysis of the block-of-eight experiment. This is done in order to be complete and assess all the influences in the breakdown process.

Different materials, as well as the other factors initially named, will be introduced into each successive experiment. The results of this program will be compiled in the form of graphs and charts for the high-voltage design engineer.

REFERENCES

1. M. M. Chrepta and G. W. Taylor, "Light Measurements in Vacuum Gaps," USAECOM Technical Report 2781, December 1966.

2. M. H. Zinn, G. W. Taylor, and M. M. Chrepta, "Influence of Electrode Material on High-Voltage Breakdown in Vacuum," USAECOM Technical Report 2901, January 1968.

3. M. J. Mulcahy, A. Watson, and W. R. Bell, "High-Voltage Breakdown Study," USAECOM Contract DA28-043 AMC-00394(E) ARPA Order No. 517.

APPENDIX

The Yates Algorithm is discussed thoroughly in Davies' Design and Analysis of Industrial Experiments. It may be illustrated simply by the following example. Assume that Table VIII represents an experimental design for performing tests at two levels of three factors:

TABLE VIII - Full Factorial Test of Three Factors at Two Levels.

Test	a. Main Effects			b. Interaction Effects			
	A	B	C	AB	AC	BC	ABC
1	-	-	-	+	+	+	-
2	+	-	-	-	-	+	+
3	-	+	-	-	+	-	+
4	+	+	-	+	-	-	-
5	-	-	+	+	-	-	+
6	+	-	+	-	+	-	-
7	-	+	+	-	-	+	-
8	+	+	+	+	+	+	+

The levels of the interaction terms are determined by multiplying the appropriate columns of the main effects. It should be noted that each of the terms contains an equal number of pluses and minuses and that none of the factors duplicates the pattern of another factor or represents any other factor multiplied by (-1). The first condition indicates that the test series is balanced for each factor, while the second condition indicates that none of the factors is confounded with each other.

After the experiment has been performed, a series of measurements of a single characteristic, X, is obtained for each of the tests, 1 through 8. The main effects and interaction effects can be determined by following the instructions contained in Table VIII and dividing the result by the number of test values. If X_1, X_2,....X_8 are the individual readings, following the instructions from row 8 back through row 1 we have:

$$A = \frac{X_8 - X_7 + X_6 - X_5 + X_4 - X_3 + X_2 - X_1}{8}$$

$$B = \frac{X_8 + X_7 - X_6 - X_5 + X_4 + X_3 - X_2 - X_1}{8}$$

etc.

While the effects can be obtained by repeatedly operating on the set of eight readings in this manner, they may be obtained more simply by following the Yates Algorithm. The procedure for the Algorithm consists of the following steps, which are shown in Table IX:

TABLE IX - Steps of the Yates Algorithm

Row \ Column	1	2	3	4	Final
1	X_1	X_2+X_1	$X_4+X_3+X_2+X_1$	$X_8+X_7+X_6+X_5+X_4+X_3+X_2+X_1$	Mean
2	X_2	X_4+X_3	$X_8+X_7+X_6+X_5$	$X_8-X_7+X_6-X_5+X_4-X_3+X_2-X_1$	A
3	X_3	X_6+X_5	$X_4-X_3+X_2-X_1$	$X_8+X_7-X_6-X_5+X_4+X_3-X_2-X_1$	B
4	X_4	X_8+X_7	$X_8-X_7+X_6-X_5$	$X_8-X_7-X_6+X_5+X_4-X_3-X_2+X_1$	AB
5	X_5	X_2-X_1	$X_4+X_3-X_2-X_1$	$X_8+X_7+X_6+X_5-X_4-X_3-X_2-X_1$	C
6	X_6	X_4-X_3	$X_8+X_7-X_6-X_5$	$X_8-X_7+X_6-X_5-X_4+X_3-X_2+X_1$	AC
7	X_7	X_6-X_5	$X_4-X_3-X_2+X_1$	$X_8+X_7-X_6-X_5-X_4-X_3+X_2+X_1$	BC
8	X_8	X_8-X_7	$X_8-X_7-X_6+X_5$	$X_8-X_7-X_6+X_5-X_4+X_3+X_2-X_1$	ABC

(1) Tabulate the eight (or, more generally, all) readings in the first column.

(2) Add reading 2 to reading 1 and tabulate in row 1 in the second column.

(3) Continue for pairs of readings until all have been added in turn.

(4) Subtract reading 1 from reading 2 and tabulate in the next row (row 5 for the specific example).

(5) Continue for pairs of readings until all have been subtracted in turn.

(6) Repeat steps 2 through 5 using the values tabulated in column 2 and tabulating the new results in column 3.

(7) Repeat step 6 using the values in column 3, tabulating the results in column 4. This completes the operations for this specific example. In general, the n operations are tabulated in 1+n columns (including the original data) where 2^n = the number of test conditions.

(8) The final tabulation when divided by the number of test conditions is the desired result. The value in each row represents the coefficient of the effect shown in the last column of Table IX. The reason why the end step in each row is equivalent to the appropriate coefficient is evident from an examination of the sum listed in the fourth column and comparing this with the instructions given for each effect in Table VIII.

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High-Voltage Breakdown in Vacuum						
Electrodes for High-Voltage Applications						